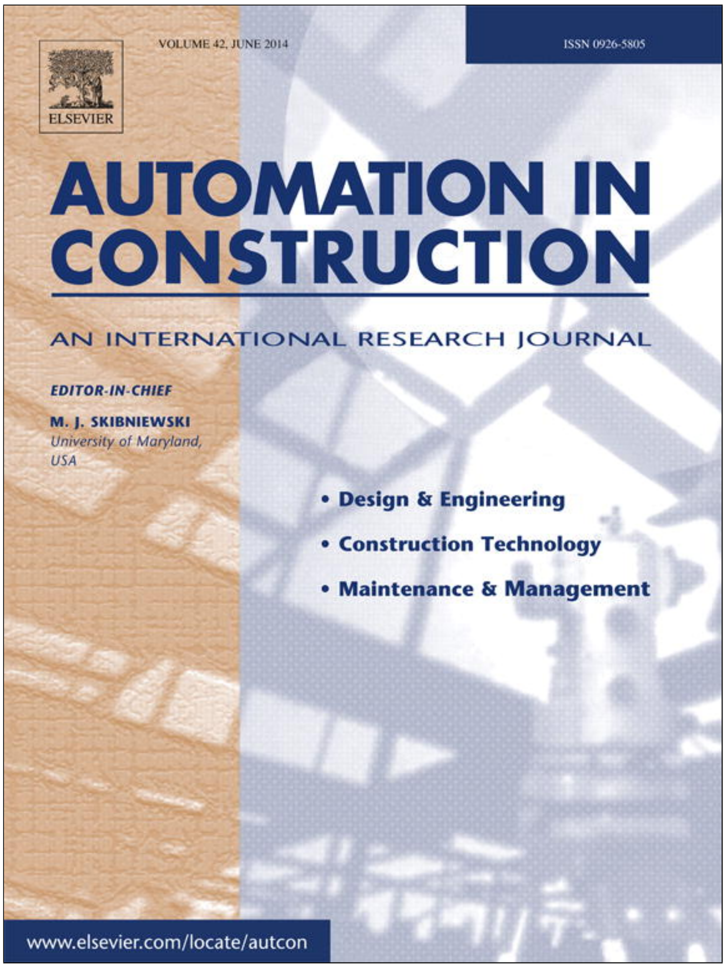
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Control of indoor CO_2 concentration based on a process model

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ABSTRACT

Air-tight buildings need to have ventilation systems, although the use of these systems results in heavy energy consumption within the building sector. For this reason they have to be adequately regulated in order to achieve good indoor air quality and lower operation costs. The main challenge is to optimize regulation in office buildings, theaters, museums, and schools, where there are large fluctuations and heavy operating costs. Each further optimization leads directly to a better indoor climate and a reduction in energy consumption. In the case of ventilation systems, PI or PID regulators are usually used. In the described research an internal model control (IMC) system was designed with an internal loop, which constantly checks the momentary CO_2 concentration, and makes the necessary adjustments to the air flow. The results showed a significant improvement in the CO_2 level when using an IMC controller, in comparison with PI controller. The desired indoor air quality is achieved more than 80% of the time, with lower operating costs.

1. Introduction

Within the EU, more than 40% of produced energy is used by the building sector, which is responsible for 35% of CO_2 emissions. At least 20% of all energy is used for the heating, cooling and ventilating of buildings (Heating, ventilation and air conditioning systems — HVAC, [16]). Over the years HVAC systems have changed significantly. While human comfort in buildings has been much improved by means of different HVAC systems, energy consumption has also risen. It is generally recognized that, while improved technical solutions are very desirable, at the same time energy consumption needs to be reduced. A number of steps have been taken in this direction, such as: improved thermal insulation of walls and roofs and improved windows, pump-heating systems and central ventilation systems. The energy consumption of buildings is the main issue. However, many of the steps which have been taken lower energy consumption also result in a decrease in the level of human comfort. For example triple glazing, which is nowadays most commonly used in new buildings, reduces the energy consumption of a building, but simultaneously reduces light transmission. It has been shown that the amount of natural light in a room has a significant effect on the productivity and well-being of people using it [6]. It has also been shown that ventilating systems or shading systems, which do not permit any user interference, are not optimal for users [22]. Such systems cannot usually respond quickly, or even at all, to changeable room conditions. Over the last decade low energy solutions have remained the main goal, but greater emphasis has been placed on human comfort and well-being.

Despite the fact that systems for thermal comfort, air-quality and lighting need to be designed and solved together [12,13],the authors have attempted to go deeper into research of only air-quality regulations, with the aim of finding regulation solutions which can respond to momentary air quality in rooms and buildings. The results of this research could be implemented in collective regulation systems.

Nowadays ventilation systems are practically indispensable in all buildings. Many researchers have found a strong correlation between ventilation strategies, indoor air quality (IAQ), and energy consumption. For instance, Budaiwi [5] compared different ventilation strategies, i.e. continuous ventilation, ventilation only during occupancy, and ventilation based on variable occupancy. He showed that in the case of ventilation only during occupancy, and ventilation based on variable occupancy, there was a decrease in energy consumption of 30% and 50% respectively, compared to continuous ventilation. It has also been shown that ventilation in buildings is often designed and used for maximum occupancy, which, realistically, is hardly ever achieved [7]. If ventilation systems are not adequately adjusted to real needs, the energy losses can be huge. Several authors have suggested that a CO_2 parameter could be suitable parameter for detecting the level of occupancy, and for the adjustment of the ventilation rate [7,11,13,14,15,21]. Different percentages of energy reduction (ranging from 10 to 50%) are cited in the case of demand control ventilation (DCV) as compared to continuous ventilation. In the U.S. Department of Energy (Energy Efficiency and Renewable Energy) a relationship has been established between the ventilation rate and the CO_2 concentration. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the ventilation rate should be set as 25.5–34 m^3/h/person. At this rate the

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CO_2 concentration in a room could not exceed 1000 ppm, which is the limit set by the ASHRAE as a standard value.

If the DCV system is selected as a regulating tool, then its effectiveness depends on the speed of its reaction to real-life changes. Some models react faster and better than others. If such models are finely tuned, it is possible to decrease energy consumption even further. The effectiveness of DCV can be an even greater role in the case of buildings where large and sudden fluctuations are expected, e.g. in museums, theaters, and galleries. The main goal is the management of fast adjustments to the ventilation rate. If this is not achieved then, despite the detection of an increased CO_2 concentration detection and the activation of the ventilation system, it might happen that the rate of ventilation is not adjusted to the real need. This could lead to a stage where a comfortable level of air conditioning (with CO_2 lower than 1000 ppm) is achieved over an excessively long response-time, or frequently not at all. Ventilation systems which have the same response whether a gallery is quite full of half empty are not appropriate.

The type of regulation used in the case of various HVAC systems differs. The use of linear regulators (proportional (P), integral (I) and also derivative (D)), as well as nonlinear regulators, or combinations of both, has been described in the literature ([2,4,12,24]). Despite the fact that HVAC systems are nonlinear systems, they can be satisfactorily controlled by means of linear regulators [10,18,19]. A method for signal filtering used in the PID controller, which significantly improve the properties of the feedback loop, has been presented by Hägglund [9]. Filters were established for the set-point, the process output, and the measurable load disturbance. By means of filters it is possible to improve process models by up to 25%. In this paper the design of a PI controller based such a process model is presented. An anti-windup mechanism was also implemented, which is needed if the control system is to function properly, and is strongly influenced by constraints. The paper is organized as follows: a problem description and mathematical model are given in Section 2, whereas in Section 3 the design of the control algorithm is presented. Simulation of control systems is presented in Section 4 and conclusions are given in Section 5.

2. Problem description and mathematical model

In all buildings where the occupancy of rooms is not constant and can fluctuate massively, e.g. schools, office buildings, theaters, and museums, the regulation of air ventilation is a difficult problem. In most cases the ventilation systems have several rates on which they can work, and these rates have pre-defined activation schedules. However, such regulation systems cannot react to momentary changes in the room. Regulation systems react on the on–off principle. They are therefore not optimal, and cannot provide healthy air conditions inside the room. Buildings are often under or over ventilated, without disregard to the real rate of occupancy. Over-ventilated buildings are not cost-effective, whereas under-ventilated buildings lead to health problems [16]. In the case of short term exposure these consist of headaches, drowsiness, lack of concentration, fatigue, nausea, and dizziness. In the case of long term exposure the health problems could be: eye, nose and throat irritations, air-way infections, and coughs. In this paper a description is given of a ventilation system which is able to regulate air flow with the aim of CO_2 reduction, according to the needs in the room. Similar models have been described by Aglan [1], and Shi et al. [17]. The model describes the changes in the CO_2 concentration in the room directly in dependence on the level of occupancy, i.e. the number of people inside the room. It includes the intake of outdoor fresh air (q), the CO_2 concentration of the outdoor air (c_0), the concentration of CO_2 exhaled by the people in the room (p), and the outflow which is equal to the intake flow (q) with current CO_2 concentration (c) (Table 1). The model is based on the assumption that the CO_2 concentration of the outdoor air is constant and known, and that the indoor reference concentration of CO_2 is also defined. The volume of the space is defined as V.

Table 1
Nomenclature.

Variable	Description	Unit
q	Outdoor fresh air intake	m^3/h
q^*	Outdoor fresh air intake in steady-state	m^3/h
q_c	Constraint signal	m^3/h
q_{min}	Minimal airflow rate	m^3/h
q_{max}	Maximal airflow rate	m^3/h
c_o	Outdoor air CO_2 concentration	ppm
c	Momentary CO_2 concentration	ppm
c^*	Concentration of CO_2 in steady-state	ppm
c_r	Reference CO_2 concentration	ppm
c_m	CO_2 concentration as the model output	ppm
ph	CO_2 concentration generated per person	ppm*m^3/hperson
p	CO_2 concentration generated by all people in the room	ppm*m^3/h
$G_m(s)$	Transfer function of the process model	
$G_r(s)$	Transfer function of the reference model	
$G_c(s)$	Transfer function of the controller	
T_r	Reference model time constant	h
V	Room model volume	m^3
N	Number of people in the room	
t	Time	h

The equation which defines the change of concentration in the room is the following:

$$\frac{dc}{dt} = \frac{c_0}{V}q - \frac{1}{V}cq + \frac{1}{V}p. \tag{1}$$

The change of CO_2 concentration depends nonlinearly on intake flow q, the indoor CO_2 concentration c, and the exhaled CO_2 concentration of the people in the room p. It can be rewritten as a nonlinear differential equation as follows

$$\frac{dc}{dt} = f(c, q, p). \tag{2}$$

The concentration c can be controlled by the intake flow q. This means that the concentration c is the controlled variable (CV), whereas the intake flow q is the manipulated variable (MV). The exhaled concentration p is not measurable, and is therefore treated as a disturbance.

3. Linearization and controller design

The design of a linear controller requires the use of a linear model of the process in the equilibrium point or in the operating point. The nonlinear model of the process is therefore described, in a linearized form as follows

$$\frac{dc}{dt} = \frac{\partial f}{\partial c}\bigg|_{(c^*,q^*)} c + \frac{\partial f}{\partial q}\bigg|_{(c^*,q^*)} q \tag{3}$$

where c^* and q^* denote the equilibrium point for concentration c and for intake flow q, respectively.

In order to define the deviation model, the equilibrium point first need to be found. This means that the derivative at this point is equal to zero, as shown:

$$f(c, q, p)\Big|_{(c^*,q^*)} = 0. \tag{4}$$

This gives us a relation between the input and output of the process when in equilibrium, or in steady-state. The relation is presented in Fig. 1 and defined in Eq. (5).

$$q^* = \frac{-p}{c_0 - c^*}. \tag{5}$$

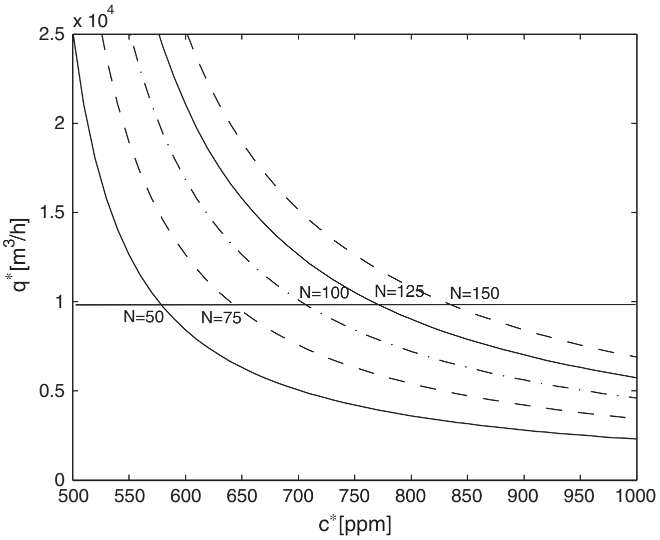

Fig. 1. The statical characteristics of the process. The relations between q^* and c^* in equilibrium point for the different number of people in the room.

The static characteristics are typically nonlinear, and vary strongly according to the number of persons inside the room.

Linearization around the equilibrium point requires the calculation of partial differentials at this point, i. e.

$$\begin{aligned}\left.\frac{\partial f}{\partial c}\right|_{(c^*,q^*)} &= \frac{p}{V(c_0-c^*)} = -\frac{q^*}{V}\\ \left.\frac{\partial f}{\partial q}\right|_{(c^*,q^*)} &= \frac{c_0-c^*}{V} = -\frac{p}{Vq^*}.\end{aligned} \tag{6}$$

This leads to the following form of Eq. (1)

$$\frac{dc}{dt} = a_p(q^*)c + b_p(q^*)q \tag{7}$$

where $a_p(q^*) = -\frac{q^*}{V}$ and $b_p(q^*) = -\frac{p}{Vq^*}$ are constant and depend on the operating point of the system q^* and the average number of people in the room N, which define the exhaled CO_2 concentration p.

This leads to a transfer function of the process at average conditions, which is described as follows:

$$G_m(s) = \frac{b_p(q^*)}{s + a_p(q^*)}. \tag{8}$$

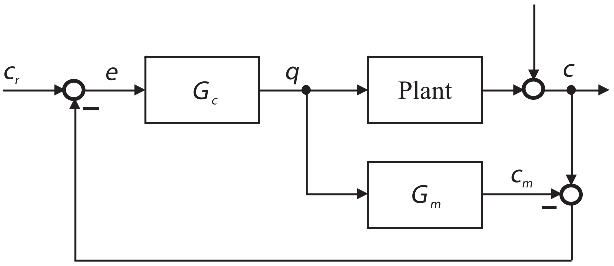

Fig. 2. The IMC control scheme.

The model is a part of an IMC controller in internal model control loop, as shown in Fig. 2. The $G_c(s)$ part of the control scheme is defined so as to cancel the plant dynamics approximately and force the system to follow the reference model which is defined as follows

$$G_r(s) = \frac{1}{T_r s + 1} \tag{9}$$

where T_r stands for the reference model time constant.

This means that IMC control requires the design of the $G_c(s)$ part, which has an input $e(t)$ defined as

$$e(t) = c_r(t) - c(t) + c_m(t)$$

and an output $q(t)$. The $G_c(s)$ part of the controller consists of linear part $G_c^o(s)$ and a nonlinear part, which is due to the constraints. The linear part is defined as an inverse process model, which is filtered by the reference model as follows

$$G_c^o(s) = \frac{s + a_p(q^*)}{b_p(q^*)} \cdot \frac{1}{T_r s + 1} \tag{10}$$

where $G_c^o(s)$ defines the transfer function between the input to the controller $e(t)$ and the output of the linear controller part defined as $q_c(t)$. The nonlinear part which introduces the constraints is defined as follows:

$$q(t) = \begin{cases} q_{min}, & q_c^o(t) \le q_{min} \\ q_c^o(t), & q_{min} \le q_c^o(t) \le q_{max} \\ q_{max}, & q_c^o(t) > q_{max} \end{cases} \tag{11}$$

where the output q_c is a constraint signal q_c^o. It is constrained between the lower q_{min} and upper bound q_{max}.

An anti-windup mechanism [20] is implicitly incorporated to the scheme by the IMC design, which makes the design and the scheme much simpler than in the case of a PI or a PID controller, where, in the case of constraints, the anti-windup mechanism needs to be added with a special scheme and an additional tuning parameter.

4. Simulation of control system and discussion

The simulation model was established for a gallery with a volume of $V = 1128$ m^3 and an expected average occupancy of 125 people, although it is expected that occupancy will actually vary between 50 and 150 people. The CO_2 outdoor concentration varies between 400 and 450 ppm, and depends on the microclimate and altitude [8]. In the studied case the outdoor CO_2 was defined as $c_0 = 450$ ppm. According to the ASHRAE standard, the CO_2 concentration in the room should be kept below 1100 ppm [3]. In our case the reference level of CO_2 concentration in the room was set to $c_r = 800$ ppm, which ensures high-quality indoor air. The exhaled CO_2 concentration in the room is defined by the number of people present N and by the concentration of exhaled CO_2 per hour is equal to 0.0052 l/s, [14], where p defines the exhaled CO_2 in the case of N people present. The inlet air is constrained to $q_{max} = 10.000$ m^3/h.

In Fig. 1 the relationship between the CO_2 concentration level c^* in the gallery and the fresh intake flow q^* in steady-state is presented. The relationship is shown for five different occupancy levels. It is common to all of them that the CO_2 concentration level decreases if the intake flow is increased. With an intake flow of q_{max} it is possible to keep this concentration below the selected reference level of 800 ppm, if the occupancy level is lower than 125 people. In the case of 150 people a level of 850 ppm can be achieved, which is still a comfortable zone with good air quality.

In Figs. 3 and 4 a room situation is described where at time zero 100 persons enter the room, and at a second step (4 h later) an additional 20, and at a third step (after 4 h) an additional 20. Twelve hours after the start of occupancy, the level drops to 105 people. The ventilation system is regulated once by means of a PI controller (Fig. 3) and once with IMC controller (Fig. 4).

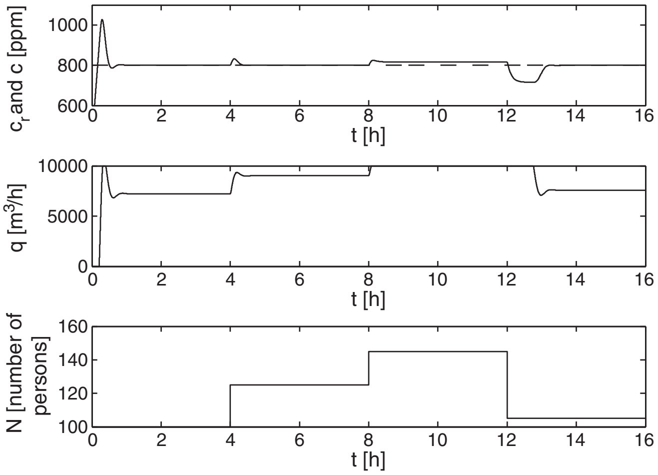

Fig. 3. The PI control of ventilation system without anti-windup.

In Fig. 3 the PI control without anti-windup is shown. The parameters of the PI controller were tuned using the classical Ziegler–Nichols tuning rules [23]. Due to the big initial increase in the occupancy level (from 0 to 100 people) The CO_2 concentration rises rapidly, and soon reaches a level of 1000 ppm. At the same time the ventilation system is activated, but it takes several minutes before the CO_2 level starts to decrease. In fact it takes somewhat less than 30 min for the CO_2 level to drop to the reference level of 800 ppm, and that in this case the ventilation operates at q_{max} for less than 8 min. In the second step (when occupancy is increased from 100 to 120 people) the ventilation rate increases by 30%, and the maximum CO_2 concentration level is increased by 14%, but only for 19 min; it then drops back to c_r again. At each increase in the occupancy level, there is also an increase in the CO_2 concentration, but this is quickly reduced by the higher ventilation rate. At the third step an additional 20 people enter the room, and the CO_2 concentration is so high that the ventilation needs to operate at its maximum operating rate. Despite the use of q_{max}, the level c_r cannot be achieved. The minimum CO_2 concentration level that can be reached is 850 ppm, which is acceptable since it is still very much below the ASHRAE limit of 1000 ppm. At step 4 the occupancy level drops suddenly to 105 people, and so does the CO_2 concentration level. The response of the ventilation system is to decrease its rate, but it takes 66 min before the CO_2 concentration reaches c_r. In the meantime the concentration was lower than necessary, which means unnecessary energy consumption. Over the whole period of 16 h of modeling, including occupancy fluctuations, the CO_2 concentration level was above c_r for 30% of the time, with a highest reached value of 1000 ppm. The ventilation system operated at q_{max} for 28% of the time.

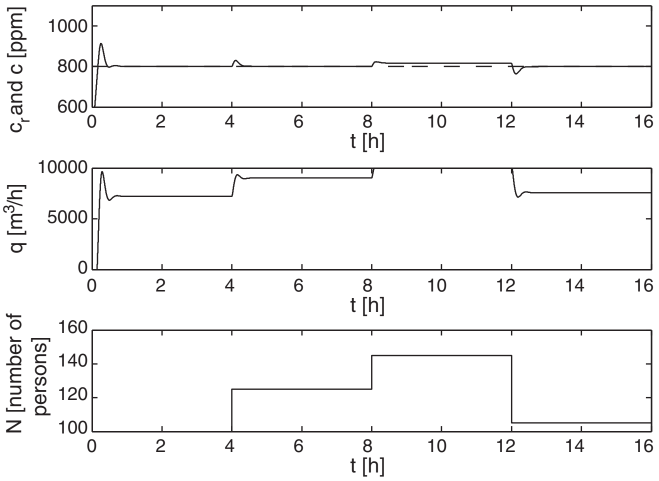

Fig. 4. The IMC control of ventilation system.

In Fig. 4 the effect of IMC control on the same operating regime as described above is presented. The occupancy level changed every two hours; i.e. to levels of 100, 120, 140 and 105 people. In the case of the high initial occupancy, there is a corresponding increase in the CO_2 concentration level, but due to the quicker response of the regulation of the ventilation system, only a level of 900 ppm was reached. After that it began to decrease with a ventilation rate which was lower than q_{max}, which was needed in the first example. When the occupancy level rises, the CO_2 concentration also rises, and increased ventilation is needed in order to achieve c_r. At the third step, when the number of people is 140, c_r cannot be achieved, neither in the case of this model. In this case q_{max} is needed in order to obtain the lowest possible concentration c. At step 4, when an immediate drop occurs in the occupancy level, the IMC control reacts quickly, so that the reference level of the variable c_r is achieved within 20 min.

If the results of the two models are compared, it is possible to define several common points, as well as several main differences between them. It is common to both models that the CO_2 concentration level rises with an increase in occupancy rise, with that it is possible to decrease the concentration c in smoothly and rapidly by proper regulation of the ventilation rate. The concentration levels in the steady-state are the same in the case of both of the control algorithms, but the time and ventilation rates needed to achieve a steady-state are different. It can be seen from the presented simulation examples that the PI controller needs more time to react to changes in occupancy, whereas the ventilation rates are higher when compared to the IMC model. In the case of the IMC controller, q_{max} is needed for 12% less time than that in the case of the PI model. The estimated reduction in energy consumption due to lower fan energy consumption and lower volume of outside air to be conditioned is about 3%. It is shown that the IMC controller reacts better to occupancy fluctuations than that the PI controller. This means that the more fluctuations occur, the greater is the difference in the efficiency of the controllers. This correlates directly with heavier energy consumption in the case of the PI control.

5. Conclusion

It has been confirmed that IMC control offers some advantages in comparison to PI control systems. It incorporates implicitly the anti-windup mechanism, which makes the design much simpler than in the case of PI controller design. The proposed control strategy provides improved sensitivity and quicker reaction to changes that occur in an observed space. In this way ventilation systems can work with the lowest possible flow rate and operating costs. By means of such regulation it will be possible to obtain better solutions for places where high occupancy fluctuation is expected, such as schools, museums, and theaters, and instant adjustment of the ventilation rate is needed.

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